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TNO Human Factors Research Institute

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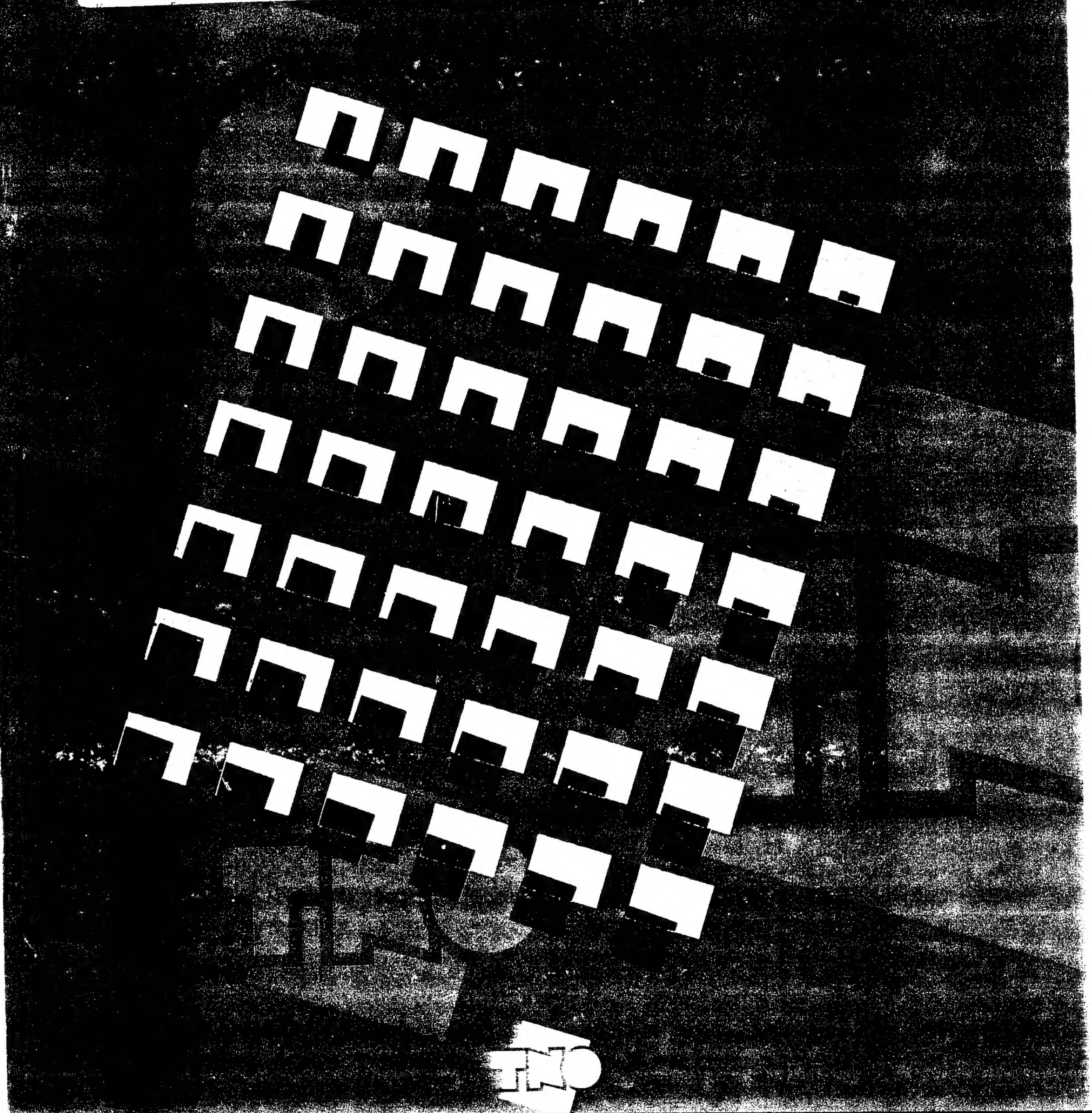
The effect of field of view and scene content on the validity of a driving simulator for behavioral research



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TNO Human Factors
Research Institute

Kampweg 5
P.O. Box 23
3769 ZG Soesterberg
The Netherlands

Phone +31 346 35 62 11
Fax +31 346 35 39 77

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authors
N.A. Kaptein
A.R.A. van der Horst
W. Hoekstra

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The effect of field of view and scene content on the validity of a driving simulator for behavioral research

11. AUTHOR(S)

N.A. Kaptein, A.R.A. van der Horst and W. Hoekstra

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

TNO Human Factors Research Institute
Kampweg 5
3769 DE SOESTERBERG

13. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Director of Army Research and Development
Van der Burchlaan 31
2597 PC DEN HAAG

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The present study addresses the effects of field of view and scene complexity on the validity of a fixed-base driving simulator with respect to braking behavior. Two driving simulator experiments were performed. The results were compared to those of a field study (Van der Horst, 1990). When approaching a stationary vehicle, subjects were instructed to brake as late as possible, without causing a collision. The instruction was either to brake "hard", or to brake "normal". Experiment 1 showed that the timing of the start of the braking maneuver was not affected by field of view and scene complexity. Yet, the coordination of the ongoing braking maneuver was more realistic with increasing field of view (120° versus 40°). In contrast to the Van der Horst (1990) study, in the present experiment drivers took larger safety margins (i.e., started to brake earlier) with higher approach speeds. This result indicates that, for the present task, perceptual information at larger distances was insufficient in the driving simulator, even with 120° FOV and a relatively complex scene. In Experiment 2 on half of the trials the image was occluded immediately after the onset of the braking maneuver, in order to investigate the use of visual information after the start of the braking maneuver. Results showed that without visual information during the braking maneuver, drivers tended to overshoot the intended stopping position more often. This result indicates that drivers use visual information during the braking maneuver in order to timely stop before the stationary vehicle.

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De huidige studie is gericht op de effecten van beeldhoekgrootte en complexiteit van de scène op de validiteit van een fixed-base rijsimulator ten aanzien van remgedrag. Twee rijsimulator-experimenten zijn uitgevoerd, waarvan de resultaten zijn vergeleken met de resultaten van een veldstudie (Van der Horst, 1990). Bij het naderen van een stilstaand voertuig werd aan proefpersonen opgedragen zo laat mogelijk te remmen, echter zonder een botsing te veroorzaken. De instructie luidde of 'hard', dan wel 'normaal' te remmen, afhankelijk van de experimentele conditie. Experiment 1 liet zien dat het timen van het begin van de remmanoeuvre niet werd beïnvloed door beeldhoekgrootte of complexiteit van de scène. Echter, de controle gedurende de remmanoeuvre was realistischer bij een grotere beeldhoekgrootte (120° i.p.v. 40°). In tegenstelling tot de resultaten van Van der Horst, gebruikten bestuurders in de huidige studie echter grotere veiligheidsmarges (i.e., begonnen eerder te remmen) bij hogere snelheden. Dit suggereert dat voor de huidige taak in de rijsimulator perceptuele informatie op grotere afstand onvoldoende was, zelfs met een beeldhoek van 120° en een relatief complexe scène. In Experiment 2 werd in de helft van de ritten het beeld geoccludeerd direct na het begin van de remmanoeuvre. De resultaten lieten zien dat zonder visuele informatie gedurende de remmanoeuvre bestuurders vaker botsingen veroorzaakten, hetgeen aantoont dat visuele informatie gedurende de remmanoeuvre wordt gebruikt om tijdig tot stilstand te komen.

CONTENTS

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Institute: TNO Human Factors Research Institute
Group: Skilled Behavior

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SUMMARY

The present study addresses the effects of field of view and scene complexity on the validity of a fixed-base driving simulator with respect to braking behavior. Two driving simulator experiments were performed. The results were compared to those of a field study (Van der Horst, 1990). When approaching a stationary vehicle, subjects were instructed to brake as late as possible, without causing a collision. The instruction was either to brake "hard", or to brake "normal". Experiment 1 showed that the timing of the start of the braking maneuver was not affected by field of view and scene complexity. Yet, the coordination of the ongoing braking maneuver was more realistic with increasing field of view (120° versus 40°). In contrast to the Van der Horst (1990) study, in the present experiment drivers took larger safety margins (i.e., started to brake earlier) with higher approach speeds. This result indicates that, for the present task, perceptual information at larger distances was insufficient in the driving simulator, even with 120° FOV and a relatively complex scene. In Experiment 2 on half of the trials the image was occluded immediately after the onset of the braking maneuver, in order to investigate the use of visual information after the start of the braking maneuver. Results showed that without visual information during the braking maneuver, drivers tended to overshoot the intended stopping position more often. This result indicates that drivers use visual information during the braking maneuver in order to timely stop before the stationary vehicle.

Het effect van beeldhoek en beeldinhoud op de validiteit van een rijsimulator voor gedragsonderzoek

N.A. Kaptein, A.R.A. van der Horst and W. Hoekstra

SAMENVATTING

De huidige studie is gericht op de effecten van beeldhoekgrootte en complexiteit van de scène op de validiteit van een fixed-base rijsimulator ten aanzien van remgedrag. Twee rijsimulator-experimenten zijn uitgevoerd, waarvan de resultaten zijn vergeleken met de resultaten van een veldstudie (Van der Horst, 1990). Bij het naderen van een stilstaand voertuig werd aan proefpersonen opgedragen zo laat mogelijk te remmen, echter zonder een botsing te veroorzaken. De instructie luidde of "hard", dan wel "normaal" te remmen, afhankelijk van de experimentele conditie. Experiment 1 liet zien dat het timen van het begin van de remmanoeuvre niet werd beïnvloed door beeldhoekgrootte of complexiteit van de scène. Echter, de controle gedurende de remmanoeuvre was realistischer bij een grotere beeldhoekgrootte (120° i.p.v. 40°). In tegenstelling tot de resultaten van Van der Horst, gebruikten bestuurders in de huidige studie echter grotere veiligheidsmarges (i.e., begonnen eerder te remmen) bij hogere snelheden. Dit suggereert dat voor de huidige taak in de rijsimulator perceptuele informatie op grotere afstand onvoldoende was, zelfs met een beeldhoek van 120° en een relatief complexe scène. In Experiment 2 werd in de helft van de ritten het beeld geoccludeerd direct na het begin van de remmanoeuvre. De resultaten lieten zien dat zonder visuele informatie gedurende de remmanoeuvre bestuurders vaker botsingen veroorzaakten, hetgeen aantoont dat visuele informatie gedurende de remmanoeuvre wordt gebruikt om tijdig tot stilstand te komen.

1 INTRODUCTION

In order to make driving in a simulator as realistic as possible, the common objective is to provide a driver with a simulated driving environment that contains the same information that is also available in real world driving. Yet, it is not necessary to provide *all* that information. As long as behavior in the simulator is more or less identical to behavior in the real world, it is acceptable to use relatively simple images to minimize data communication and computer processing time, and, for instance, to allow for an optimal image resolution and refresh rate. Such decisions depend on which aspects of visual information are relevant, given a specific driving task. A direct comparison of behavior in the field and in a driving simulator on a specific driving task is necessary to judge the validity of that simulator for that task. In the present study, carried out under contract to the Dutch Royal Army, a fixed-base driving simulator was validated against real-world performance (Van der Horst, 1990) for different amounts of visual information. By this means the effect is investigated of the amount of visual information on driving simulator validity.

It is meaningless to speak of the validity of a simulator as such. Validity can only be defined with regard to a specific research question (Kaptein, Theeuwes & Van der Horst, 1995). To the extent that behavior on a task in a driving simulator is similar to behavior on that task in reality, the simulator is valid with regard to that particular task. A distinction can be made between absolute and relative validity. If one would want to investigate the effects of changes in road design on driving speed, a simulator is said to be absolutely valid with respect to the research question if the amount of speed reduction obtained in the simulator is similar to the amount of reduction that will occur in reality. If only the direction and relative size of effects of different measures is similar to in reality, the simulator is said to be relatively valid.

There are no specific guidelines available on the required level of scene complexity and field of view. With regard to scene complexity, one might like to include all objects that are visible in an outdoor scene in the corresponding simulator image, providing a scene that is as complex as the simulated reality. However, even sophisticated imaging systems can only present a fraction of the number of objects that are visible in a common outdoor scene (Clapp, 1985). It is unclear how many elements a scene must contain (e.g., AGARD, 1980) in order to obtain realistic driving behavior. It may be important to provide a driver with sufficient depth information, for example through the presence of objects of known size. The precise shape and color of objects has been suggested to be of less importance (Padmos & Milders, 1994). With regard to the driver's field of view there also is a lack of systematic research. In driving simulators particularly the size of the horizontal field of view is assumed to be important (Padmos & Milders, 1994). The specific requirements will largely depend on the characteristics of the vehicle that is simulated, and on the specific driving task. Padmos & Milders (1994; Haug, 1990) suggested that a vertical field of view of 40° would be sufficient for driving simulators. Note that the vertical field of view from a real vehicle (and consequently the effective vertical field of view in a simulator's car mock-up) is often less (Van der Horst, Vos & Padmos, 1990). This suggests that a vertical field of view of 30° might also be acceptable. On a curved road a larger horizontal field of view will provide the driver with a larger preview distance. In addition, both on a straight and on a

curved road speed and distance perception are likely to be superior with a large horizontal field of view, due to the increase of the amount of reference information and the stronger optic flow stimulus.

In order to investigate whether improving the quality of visual information increases the validity of driving simulators, the present study focuses on a task that requires detailed and accurate perception of information: braking as late as possible for a stationary vehicle. In a field study, Van der Horst (1990) had subjects brake as late as possible when driving towards a stationary vehicle that was positioned on a runway. In the present study the Van der Horst (1990) experiment was replicated in a simulator for two levels of both scene content and field of view. The results of this study will show to what extent the validity of the simulator for this particular task depends on the amounts of scene content and field of view.

To avoid collisions with other vehicles, an automobile driver continuously needs to judge whether it is necessary to slow down or even stop the vehicle. It has been suggested that to guide a braking maneuver drivers use the *Time-To-Collision* (TTC; Lee, 1976), the time that would pass before they would collide with the other vehicle if no action were taken, i.e., under the assumption of a constant relative speed. Lee showed that drivers could use TTC in detecting to be on collision course, in judging when to start braking, and in controlling the ongoing braking maneuver. He considered different traffic situations, and suggested that TTC might be important to traffic safety in a variety of circumstances. A major contribution of Lee's paper was the acknowledgement that the time to contact with an approaching or approached object can be derived directly from the retinal image (see also Heuer, 1993; Kaiser & Mowafy, 1993; Tresilian, 1993, 1994), and the recognition that time-based parameters are potentially effective to control dynamic interaction in traffic (see also Godthelp, 1984). Lee identified several possible functions of TTC information when driving a car.

To detect being on collision course

A driver is on collision course with a lead vehicle if, and only if, maintenance of the current level of acceleration or deceleration would result in a collision (Lee, 1976). TTC can be used to judge whether, when closing in on a lead vehicle, the current level of deceleration is sufficient to avoid a collision. Note that the observation to be on collision course does not necessarily imply that immediate action is required.

Judging when to start braking

Drivers could use a fixed TTC criterion to determine whether a traffic situation is dangerous and requires immediate action (Lee, 1976): As soon as the TTC drops below a criterion level, the driver starts to brake. This decision only requires TTC information, without any need to judge speed or distance. Yet, such an account assumes that drivers use one single TTC criterion irrespective of approach speed. The driver would start to brake, e.g., 8 s before calculated impact, independently of whether approaching a stationary vehicle with 30 or 120 km/h. Yet, assuming a constant level of deceleration, it takes four times as long to

stop when approaching with 120 km/h compared to with 30 km/h. Assuming a fixed TTC criterion implies that drivers would choose different levels of deceleration dependent on approach speed.

Controlling the braking maneuver

Another proposed function of TTC concerns the control of a braking maneuver after its onset. Like a constant TTC can be used to decide whether the situation is safe before the braking maneuver, similarly the safety of a braking maneuver can be judged in terms of TTC. As soon as TTC drops below a criterion level, it is decided that braking needs to be more powerful. This idea predicts that the observed minimal TTC (TTC_{min}) during a braking maneuver is constant across approach speeds (and equals the criterion level). Analogously to when applied to the onset of braking, such a strategy assumes that the criterion level for judging a maneuver to be safe is fixed across approach speeds.

Following distance

Analogously to when braking for a stationary vehicle, TTC may be used to determine a safe following distance when following a lead vehicle: the situation is considered "safe" as long as the TTC is larger than a certain criterion value. Note that close following distances do not necessarily imply small TTCs. As long as speed differences are very small, a close following distance is compatible with a relatively large TTC.

In summary, Lee (1976) proposed that TTC is the primary criterion to determine the safety of a traffic situation. The attractivity of this model was in the fact that only one perceptual variable is required to judge safety. Alternative models need at least two measures to control behavior in traffic. At the same time, however, this simplicity entails a possible shortcoming of Lee's model. By assuming a constant TTC criterion across approach speeds, it burdens the driver with a strategy that is either inefficient at lower speeds or otherwise dangerous at high speeds. At the cost of a second variable (speed or distance) this problem may be overcome.

Janssen, Michon and Harvey (1976) provided support for Lee's ideas, showing that drivers *are* sensitive to the approaching or receding movement relative to a lead vehicle. They also showed that a viewing time of 2 s was sufficient for an optimal perception of direction of movement, while a viewing time of only 0.5 s was sufficient to detect TTCs larger than about 6 s, irrespective of approach speed. These findings suggest that TTC is perceived fast enough to be used on-line in a dynamic environment for control of the interaction with other traffic.

It has been suggested that the cues that are used to guide a braking maneuver may differ across drivers. In a field study, Malaterre, Peytavin, Jaumier and Kleinmann (1987) instructed subjects to indicate the latest moment that they judged to be able to safely stop the car while approaching a stationary line that was marked by cones. Approach speeds ranged from 40 to 120 km/h. Results showed that TTC at the moment that the subjects would have started to brake (TTC_{br}) increased linearly with approach speed, which argues against Lee's

proposal of a constant TTC criterion. Yet, Malaterre observed differences in strategy across subjects. Some used a constant TTC_{br} over speed, others did not. It is unclear if similar differences in strategy occur during real braking. Moreover, since in the Malaterre *et al.* (1987) study no actual braking was involved. subjects did not receive feedback on the consequences of their decisions (see also Van der Horst, 1990). Such feedback might lead to more consistent results.

A more extensive test of Lee's theory was performed by Van der Horst (1990, 1991). To test Lee's (1976) suggestion that a constant TTC criterion is used for the start as well as the control of the braking process, he instructed subjects to brake as late as reasonably possible without colliding with the mock-up of a car that was positioned on collision course. Results showed that TTC_{br} increased with approach speed (similar to the findings of Malaterre *et al.*, 1987), suggesting that for different approach speeds different TTC criteria were used. This finding was not in line with Lee's (1976) hypothesis. The observed stronger deceleration with increasing approach speed was insufficient to allow for the constant TTC_{br} that was predicted by Lee. Van der Horst also showed that the minimal TTC subjects allowed to occur during a braking maneuver (TTC_{min}) was independent of approach speed, driving experience or braking instruction, indicating that a constant TTC criterion was used to control the *ongoing* braking maneuver. This latter finding was in accordance with the Lee (1976) model.

In summary, results so far do not make clear whether speed, TTC and/or distance are important to braking behavior. A combination of any two out of these three cues is sufficient to explain the observed behavior. The importance of field of view and scene content are likely to depend on the type of visual information that is used. Speed, distance and TTC may be affected by the field of view of the image to the extent that the optic flow stimulus is used. Scene content may affect distance perception and, like field of view, the optic flow stimulus. In the present study the primary aim is not to distinguish between these options, but merely to assess the importance of scene content and field of view to the validity of a driving simulator for studying braking behavior. If a larger field of view increases the validity of the driving simulator for this particular task it is expected that for 120° field of view behavior is more realistic than for 40°. Similarly, if a higher scene complexity increases the validity of the driving simulator for this particular task, it is expected that with a complex scene behavior is more realistic than with a simple scene.

2 EXPERIMENT 1: BRAKING BEFORE A STATIONARY VEHICLE

2.1 Introduction

Previous research has shown that to some extent driving behavior is similar in a simulator compared to in real traffic (see, e.g., Riemersma, Hoekstra & Van der Horst, 1988; Van der Horst & Hoekstra, 1992; Tenkink & Van der Horst, 1991; Kaptein, Theeuwes & Van der Horst, 1995), although the absolute level of the driving speed chosen is higher in a simulator than in reality (Blaauw, 1984; Tenkink, 1990). It is expected, therefore, that

braking behavior in a simulator differs in some respects to behavior in reality. In the present experiment, modelled after Van der Horst (1990), performance with different levels of field of view and scene complexity was assessed and compared to the results of the Van der Horst field study. Like in the Van der Horst study, subjects performed both "normal braking" and "hard braking" maneuvers.

2.2 Method

Subjects

Twelve paid male subjects participated in Experiment 1. All subjects had their driving license for at least five years, driving a minimum of 10,000 km/year. Subjects were between 25 and 45 years of age.

Apparatus and stimulus material

The experiment was carried out in the fixed-base driving simulator of the TNO Human Factors Research Institute. The driving simulator consists of three subsystems:

- the supervisor computer (PC, 80486 microprocessor, 33 MHz clock frequency), that controlled the communication with the other subsystems and with the experimenter, monitored the experiment and stored the data,
- the vehicle model computer (PC, 80486 microprocessor, 33 MHz) that continuously calculated the position of the virtual vehicle. The virtual vehicle had the dynamic characteristics of a Volvo 240 passenger car,
- the computer generated image (CGI) system (Evans & Sutherland ESIG 2000; refresh rate: 60 Hz, update frequency 30 Hz; delay compensation active).

Subjects were seated in a fixed-base car mock-up, the modified frame of a Volvo 240 passenger car, and used all normal controls (with automatic transmission). Based on the control signals the vehicle model computed the state of the vehicle model (for an elaborated description see Godthelp, Blaauw & Van der Horst, 1982). Feedback of steering forces was given to the driver by means of an electrical torque engine. An electronic sound generator was used to mimic the noise of engine, wind and tires. Virtual vehicle position and heading angle were transmitted via the supervisor to the visual scene computer. The CGI system computed the visual scene as seen from the position of the driver (image resolution: 25.6 × 34.1 pixels/degree of visual angle). On a projection screen the image was projected by means of three Barcographics 801 projectors (visual angles of the separate projectors: 40° horizontally and 30° vertically). The experimenter was seated in a room next to the mock-up room, where he had access to the control system, and watched the mock-up room by means of a video system. An intercom system was used for communication with the subjects.

The database consisted of a straight road; either a bare, textured road without any scenery (like a landing strip on an airport: the simple scene) or a delineated, textured road with trees, delineator posts and houses along the road (the complex scene). Each type of road was

presented in two field of view conditions. Fig. 1 shows examples of the four types of stimuli.

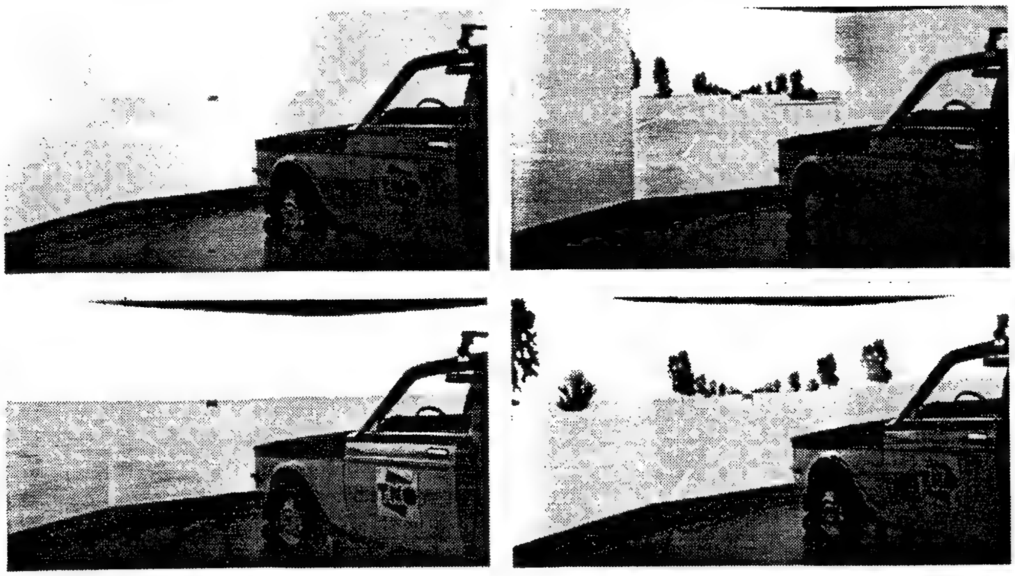

Fig. 1 Examples of stimulus road scenes: Simple scene with 40° FOV (top left panel), complex scene with 40° FOV (top right), simple scene with 120° FOV (bottom left) and complex scene with 120° FOV (bottom right).

Task

Subjects started each run by pressing the accelerator pedal so that their vehicle accelerated until they had reached their dedicated target speed, when the supervisor computer took over control and kept speed at the target level until the onset of the braking maneuver. At a distance that would be reached after a 45 s drive at the target speed, a stationary vehicle was parked on collision course. Subjects were driving with a small but variable sidewind during all of the trials, and had to keep the vehicle approximately in the center of the lane. Subjects were instructed to brake as late as possible without colliding with the stationary vehicle or blocking their wheels. They received a written instruction, in which they were instructed to brake "normal" or to brake "hard", without adjusting the braking force during the braking maneuver.

Procedure

Four different target speeds were used (30, 60, 90 and 120 km/h), as well as two levels of scene complexity (simple and complex scene) and two sizes of horizontal Field Of View (40° and 120° FOV). Each trial was replicated three times within each block. Braking instruction was varied between blocks. Half of the subjects started with the "normal braking"-instruction, the other half with the "hard braking"-instruction. In each condition subjects performed a warm-up session of 8 randomly selected trials.

In each block of experimental trials subjects responded to 4 (speeds) × 2 (scenes) × 2 (FOV) × 3 (replicas) = 48 trials, making a total of 96 trials. In each block the trials were presented in a random order, except for that the replicas were blocked within each block of trials. Except for that the occurrence of a collision was apparent in the visual image, subjects did not receive any feedback on their performance.

2.3 Results

To minimize training effects and to have the amount of practice comparable to in the Van der Horst (1990, 1991) experiment, the first experimental session was considered a training session, so that all reported data only reflect performance in sessions 2 and 3. For sessions 1, 2 and 3, 9.4%, 6.8% and 6.5% of the trials ended with a collision, respectively. These trials were not excluded from the analyses, unless if indicated otherwise.

Subjects' mean TTC_{br} (the TTC at the onset of the braking maneuver), TTC_{min} (the minimal TTC that occurred during each braking maneuver), ACC_{min} (minimal acceleration) and $DIST_{stop}$ (distance from the other vehicle when stopped) were submitted to separate ANOVAs with instruction (normal and hard braking), scene complexity (simple and complex scene), field of view (40° and 120°) and approach speed (30, 60, 90 and 120 km/h) as main factors. T-tests were performed to test whether behavior at 30 km/h and the effects of approach speed on driving behavior (the slopes of the respective functions of approach speed) in the present experiment were significantly different from in the Van der Horst (1990) study. In case effects were found of field of view or scene content, separate t-tests were performed for each of the four combinations of field of view and scene content.

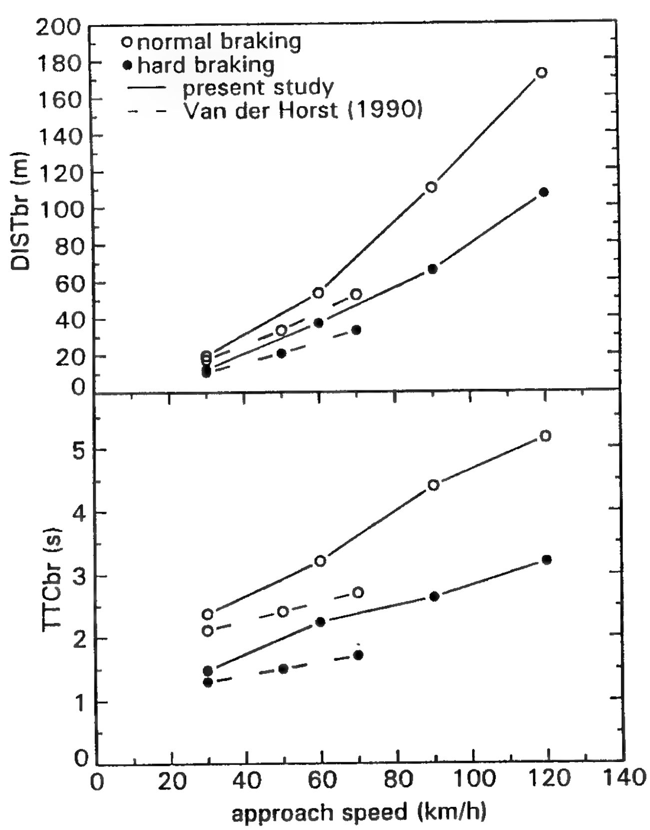

Fig. 2 $DIST_{br}$ (top panel) and TTC_{br} (bottom) as a function of approach speed, separately for normal and hard braking instructions in the present experiment, averaged over field of view and scene content (continuous lines), and in the Van der Horst (1990) study (dashed lines).

In Fig. 2 mean TTC_{br} and $DIST_{br}$ (the distance to the stationary vehicle at the onset of braking) are plotted against approach speed, collapsed over field of view and scene content. To exclude outliers and technical errors from the analysis, TTC_{br} longer than 10 s were excluded from the analysis, which led to a loss of 0.8% of the trials. As expected there was a significant main effect on TTCbr of approach speed [$F(3,33)=71.7$, $p<0.01$] and of instruction [$F(1,11)=62.8$, $p<0.01$]. TTC_{br} increased with approach speed and subjects started to brake earlier when instructed to brake "normally" compared to when instructed to brake "hard". The interaction between approach speed and instruction was also significant [$F(3,33)=5.7$, $p<0.01$]. There were no effects on TTC_{br} of field of view or scene complexity. TTC_{br} increased more with approach speed in the normal braking condition than in the hard braking condition. A t-test showed that both for normal and hard braking TTC_{br} at 30 km/h were not significantly different from the Van der Horst (1990) results [$t(22)=0.9$ and $t(22)=0.4$, respectively]. Yet, the effect of approach speed on TTC_{br} was larger in the present study, both for normal [$t(22)=3.6$, $p<0.01$] and hard braking [$t(22)=2.8$, $p<0.05$]. $DIST_{br}$ was calculated for each condition from the corresponding TTC_{br}.

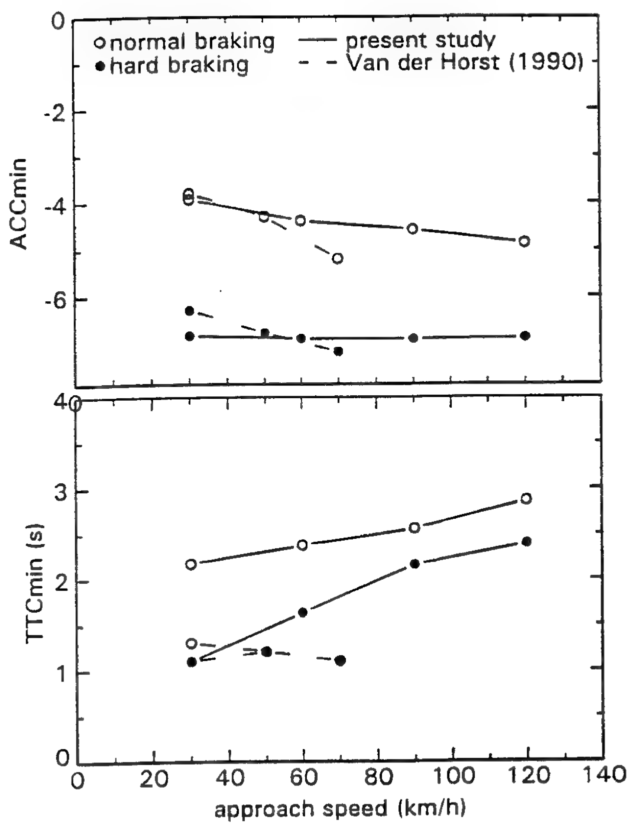

Fig. 3 ACC_{min} (top panel) and TTC_{min} (bottom) as a function of approach speed, separately for normal and hard braking instructions and 40° and 120° field of view, collapsed over scene content (continuous lines), and in the Van der Horst (1990) study (dashed lines).

In Fig. 3 mean TTC_{min} (the mean minimal TTC that occurred during a braking maneuver) and ACC_{min} (the mean minimal acceleration, or maximum deceleration, that occurred during a braking maneuver) are plotted against approach speed, separately for each instruction condition. To exclude outliers and technical errors, all TTC_{min} longer than 7 s were discarded from the analysis, which led to a loss of 0.9% of the trials. Trials ending with a collision were excluded from the analysis. There were significant main effects on TTC_{min} of

approach speed [$F(3,33)=6.4$, $p<0.01$], of instruction [$F(1,11)=12.0$, $p<0.01$] and of Field of View [$F(1,11)=4.8$, $p<0.05$]. As was expected TTC_{min} was higher with normal compared to hard braking. Unlike the Van der Horst (1990) results, TTC_{min} increased with approach speed. TTC_{min} increased with Field of View. The interaction between approach speed and instruction was also significant [$F(3,33)=3.1$, $p<0.05$]. TTC_{min} increased more with approach speed in the hard braking condition compared to the normal braking condition. These results suggest that, if TTC_{min} is regarded as an indication for the safety margin that is used when approaching a stationary vehicle, subjects needed a larger safety margin at higher approach speeds, and a smaller safety margin with larger field of view. All of the effects were qualitatively similar if for trials ending with a collision a zero TTC_{min} was used for the analyses (like in the Van der Horst study), showing that differences between the present data and the Van der Horst results cannot be attributed to the exclusion of collision trials. T-tests showed that, compared to the present results, TTC_{min} at 30 km/h was significantly lower in the Van der Horst study for normal braking [$t(22)=3.0$, $p<0.01$; $t(22)=3.2$, $p<0.01$; $t(22)=3.0$, $p<0.01$; $t(22)=2.2$, $p<0.01$, for 40°-complex scene, 40°-simple scene, 120°-complex scene, 120°-simple scene, respectively] but not for hard braking, except for with 40°-complex scene [$t(22)=2.1$, $p<0.05$]. The effect of approach speed was larger in the present study than in the Van der Horst study, both for normal braking [$t(22)=3.4$, $p<0.01$; $t(22)=2.2$, $p<0.05$; $t(22)=3.7$, $p<0.01$; $t(22)=3.8$, $p<0.01$] and for hard braking [$t(22)=2.8$, $p<0.05$; $t(22)=2.5$, $p<0.05$; $t(22)=3.0$, $p<0.01$; $t(22)=4.1$, $p<0.01$]. These findings suggest that a braking maneuver that starts relatively close to the stationary vehicle (30 km/h, hard braking) is not more difficult in the simulator than in the field, whereas maneuvers that start further from the stationary vehicle are relatively more difficult in the simulator. This finding is not different across conditions of visual information.

There was a significant main effect on ACC_{min} of approach speed [$F(3,33)=8.4$, $p<0.01$] and of instruction [$F(1,11)=102$, $p<0.01$]. ACC_{min} decreased with approach speed and was lower with normal compared to hard braking, which shows that subjects complied with the different braking instructions. The interaction between approach speed and instruction was also significant [$F(3,33)=13.1$, $p<0.01$]. ACC_{min} decreased more with approach speed in the normal braking condition compared to in the hard braking condition. No differences from the Van der Horst (1990) results were found for ACC_{min} [normal braking: $t(22)=0.5$, hard braking: $t(22)=0.1$]. Yet, effects of approach speed on ACC_{min} were significantly smaller in the present study [$t(22)=5.7$, $p<0.01$ and $t(22)=2.3$, $p<0.05$, respectively]. This result is in accordance with the increase of TTC_{br} and TTC_{min} with approach speed, since if drivers use larger safety margins, there is less need for extreme decelerations.

In Fig. 4 mean stopping distance (distance to the stationary vehicle after the approaching vehicle had been stopped) is plotted against approach speed, separately for each level of scene complexity and FOV. There was a significant main effect on stopping distance of approach speed [$F(3,33)=31.1$, $p<0.01$]. Subjects stopped further from the stationary vehicle with higher approach speeds. Also, the interaction of scene complexity and FOV was significant [$F(1,11)=6.4$, $p<0.05$], as was the interaction of scene complexity, FOV and approach speed [$F(3,33)=3.6$, $p<0.05$]. Qualitatively these effects showed to be the same when, in case a collision occurred, still the actual (negative) stopping distance was included

in the analyses (like in Van der Horst, 1990). Unlike the Van der Horst (1990) results, stopping distance increased with approach speed.

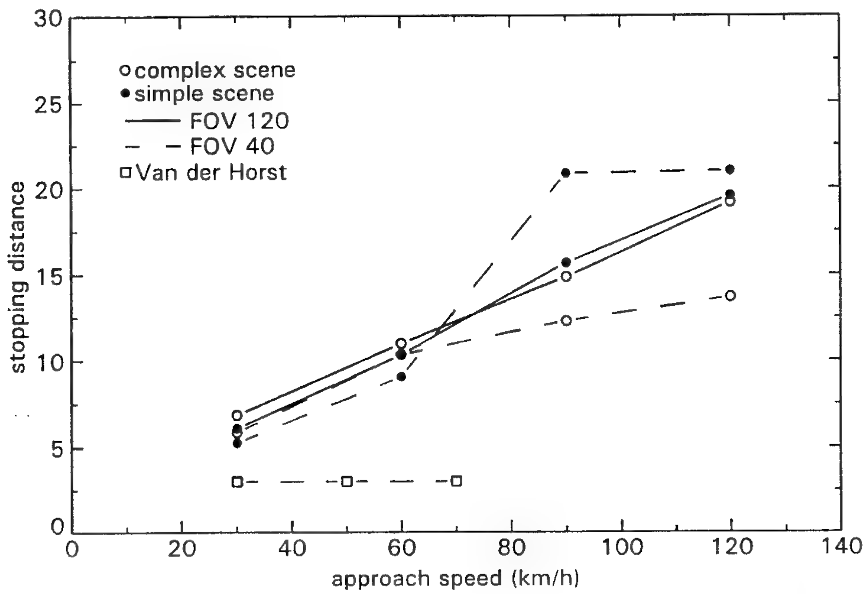

Fig. 4 Stopping distance as a function of approach speed, separately for simple and complex scenes and for 40° and 120° FOV, in the present experiment (open and closed circles), and in the Van der Horst (1990) study (open squares).

In addition, with a simple scene stopping distance decreased with FOV, whereas with a complex scene stopping distance increased with FOV. This effect increases with approach speed. It is unclear how to interpret this interaction.

Table I The percentages of collisions in Experiment 1 (sessions 2 and 3), separately for the different approach speeds and braking instructions.

speed (km/h)	normal braking		hard braking	
	40° FOV	120° FOV	40° FOV	120° FOV
30	0.00	0.00	4.17	0.00
60	2.08	0.00	10.42	8.33
90	2.17	8.33	14.58	4.17
120	10.42	14.58	18.75	8.33

Table I shows the mean percentage of collisions for each combination of approach speed and braking instruction. Effects on collision rate were analyzed by means of a log-linear analysis with scene complexity, field of view, approach speed and instruction as main factors. There were significant effects on collision score of instruction ($\chi^2[1]=57.7$, $p<0.01$), approach speed ($\chi^2[1]=25.8$, $p<0.01$) and field of view ($\chi^2[1]=4.2$, $p<0.01$), but not of scene

complexity. More collisions occurred with higher speeds, with hard braking compared to normal braking (see also Table I), and with a 40° FOV compared to a 120° FOV (8.0% versus 5.5%), suggesting that the braking maneuver was adjusted better while approaching the stationary vehicle with the 120° FOV. Note that TTC_{min} decreased with field of view: in spite of using smaller safety margins, with a larger field of view less accidents occur.

2.4 Discussion

The increase of TTC_{min} with approach speed shows that larger safety margins were used in case of higher approach speeds, suggesting that the accuracy of the perception deteriorated with approach speed, resulting in more conservative braking behavior. The results of Van der Horst (1990, 1991) that are relevant to the present study were added to Figs 2, 3 and 4. As is obvious in Fig. 3, the global level of deceleration (i.e., ACC_{min}) was similar in the present study and in the Van der Horst (1990, 1991) experiment, showing that the instructions to break normal and hard have been interpreted in a similar way, and that it is meaningful to compare the results.

The primary aim of the present experiment was to investigate the extent to which a larger FOV and a higher scene complexity in the driving simulator would make braking behavior more comparable to braking behavior in the real world. Results showed that with a 120° field of view a smaller safety margin was used, whereas less accidents occurred compared to a 40° field of view. These findings suggest that field of view is important *during* the braking maneuver. In all conditions results differed both quantitatively and qualitatively from the results of the Van der Horst (1990) field study. Yet, the difference in TTC_{min} was less with a 120° field of view. There was no clear effect of scene complexity.

Since no main effects on TTC_{br} or $DIST_{br}$ were found of field of view or scene complexity, and neither of these variables was involved in any significant interaction, it can be concluded that FOV and scene complexity are not very important for the timing of the start of a braking maneuver.

To test whether the present results were different from the results of Van der Horst (1990) t-tests were performed, for each variable comparing behavior at 30 km/h as well as the effects of approach speed. The general pattern of these comparisons is clear: results at 30 km/h in the present study were not different from the Van der Horst (1990) results, in all cases with hard braking, and in some cases also with normal braking. However, significant differences exist with regard to approach speed. Both studies obtained an effect of approach speed on TTC_{br} (and $DIST_{br}$). Yet, this effect was larger in the present study: With an approach speed of 30 km/h the TTC_{br} is similar across the two experiments, but in the present experiment TTC_{br} increases faster with approach speed than in the Van der Horst (1990) experiment. In addition, in the Van der Horst experiment TTC_{min} was constant across approach speeds, but TTC_{min} decreased with approach speed in the present experiment. Also, the decrease of ACC_{min} with approach speed that was reported by Van der Horst was not found in the present experiment. Note that, when using a single TTC_{min} criterion in all conditions during the braking maneuver, as in Van der Horst's (1990) study, different levels of deceleration

will be required for different approach speeds. Thus, in the present experiment drivers started to brake earlier in case of high approach speeds, the level of required deceleration was less severe, and during the braking maneuver a larger safety margin (TTC_{min}) was applied.

The obtained pattern of results suggests that, specifically for high driving speeds or at larger distances, subjects had difficulty in the perception of the information that they used to decide when to start braking. Even with a 120° field of view both quantitative and qualitative differences were found.

There are several possibilities to explain these findings. First, due to the limited resolution of the simulator image, speed, distance and TTC were relatively difficult to perceive. Such a problem specifically affects performance with high driving speeds, since larger distances are involved. Second, the lack of proprioceptive self-motion information in the fixed-base driving simulator may have made speed perception more difficult. Since the self-motion stimulus is larger for higher speeds, an increase in task difficulty would be predicted with high approach speeds.

3 EXPERIMENT 2: THE CONTROL OF A BRAKING MANEUVER

3.1 Introduction

Experiment 1 primarily addressed the visual information that is used *at the onset* of the braking maneuver, used for the strategic decision when to start braking. Experiment 2 focussed on the function of visual information that is available *during* the braking maneuver. The results of Experiment 1 suggested that the field of view is important during the braking maneuver. The lack of any effect of field of view on the timing of the onset of a braking maneuver suggests that the extra information provided by a larger field of view could not be used at larger distances. This hypothesis predicts that if the image is occluded after the onset of the braking maneuver, there should be no effect of field of view on any of the variables. On the other hand, if the information is available at the onset of the braking maneuver, the effects of field of view as obtained in Experiment 1 are also expected to be found if the image is occluded at the start of the braking maneuver. Experiment 2 replicated the normal braking conditions of Experiment 1. In addition, on half of the runs the image was occluded immediately after the onset of the braking maneuver. Since, except for driving speed, subjects did not receive any feedback on their performance when the image was occluded, they completed their braking maneuver on the basis of the information that was available when they started to brake.

3.2 Method

Subjects

Thirteen paid male subjects participated in Experiment 2. All subjects had their driving license for at least five years and drove a minimum of 10,000 km a year. Subjects were between 25 and 45 years of age. One subject went ill when driving in the simulator; the thirteenth subject was used to replace him, so that only twelve data sets were actually collected.

Apparatus and stimulus material

The apparatus and stimulus material were identical to in Experiment 1, except for that in the occlusion condition the image was occluded immediately after the onset of the braking maneuver.

Task

The task was similar to in the normal-braking condition of Experiment 1. Subjects, receiving a written instruction, were instructed to brake as late as possible, but without colliding with a stationary vehicle. Subjects had to use a "normal" braking strategy.

Procedure

The procedure for Experiment 2 was similar to the procedure for Experiment 1. This time only the "normal braking"-instruction was used, and on half of the trials the image was occluded at the onset of the braking maneuver. Image occlusion was randomly varied within blocks. Consequently, the experiment consisted of 4 (speeds) $\times$ 2 (scenes) $\times$ 2 (FOV) $\times$ 2 (occlusion) $\times$ 3 (replicas) = 96 trials. The trials were presented in random order. Subjects were provided with the opportunity for a break in the middle of each session. They performed a warm-up session of 8 randomly selected trials.

3.3 Results

Like in Experiment 1, the first session was considered a training session, so that all reported data reflect performance in sessions 2 and 3.

Subjects' mean TTC_{br}, TTC_{min}, ACC_{min} and $DIST_{stop}$ were submitted to separate ANOVAs with occlusion (full vision and occluded image), scene complexity (simple and complex scene), field of view (40° and 120° FOV) and approach speed (30, 60, 90 and 120 km/h) as main factors. In Fig. 5 TTC_{br} and $DIST_{br}$ are plotted against approach speed.

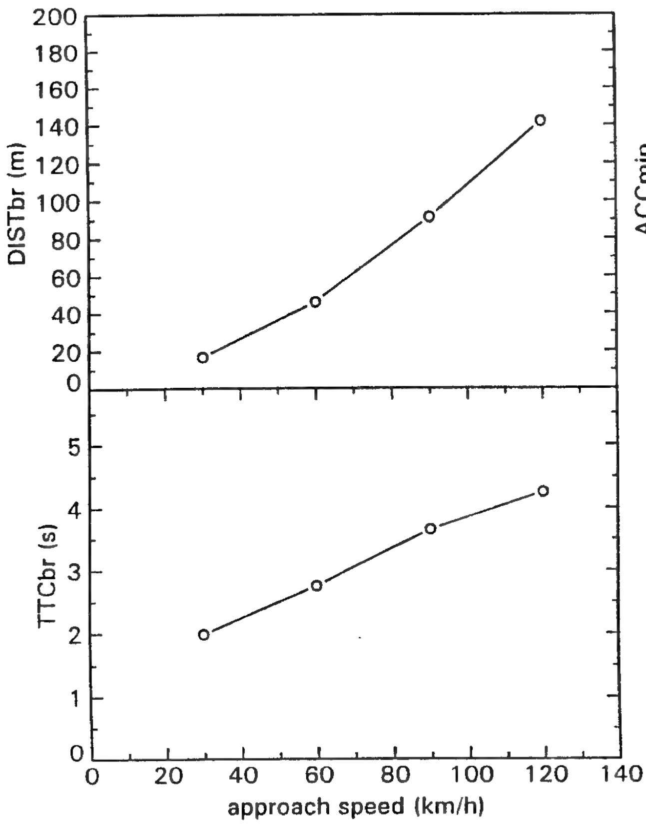

Fig. 5 $DIST_{br}$ (top panel) and TTC_{br} (bottom) as a function of approach speed in Experiment 2.

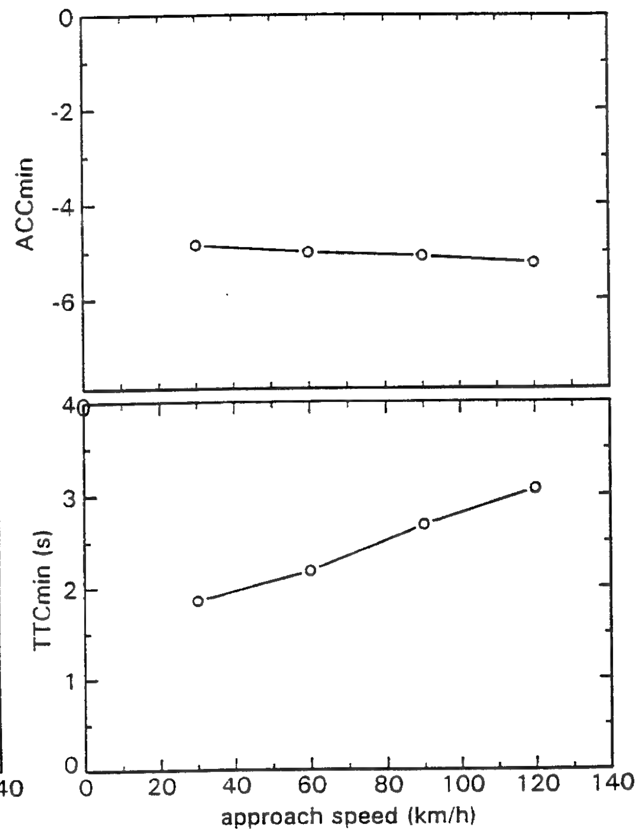

Fig. 6 ACC_{min} (top panel) and TTC_{min} (bottom) as a function of approach speed and occlusion condition in Experiment 2.

As in Experiment 1, TTC_{br} longer than 10s were considered errors and were excluded form the analysis, which led to a loss of 0.5% of the trials. There was a significant main effect on TTC_{br} of approach speed [$F(3,33)=91.8$, $p<0.01$]. TTC_{br} increased with approach speed. Note that no effect of occlusion on TTC_{br} was expected, since subjects did not know until after the onset of the braking maneuver whether the image would be occluded.

In Fig. 6 mean TTC_{min} and ACC_{min} are plotted against approach speed. All TTC_{min} longer than 7s were excluded from the analysis, which led to a loss of 0.4% of the trials. There was a significant main effect on TTC_{min} of occlusion condition [$F(1,11)=189$, $p<0.01$]. TTC_{min} was higher without occlusion. A separate ANOVA, including only the results of the no-occlusion runs, yielded a main effect of approach speed as well [$F(3,33)=3.9$, $p<0.05$], showing that like in Experiment 1, TTC_{min} increased with approach speed if the image was not occluded. There were main effects of approach speed [$F(3,33)=3.3$, $p<0.05$] and occlusion condition [$F(1,11)=6.5$, $p<0.05$] on ACC_{min} (see Fig. 6). ACC_{min} was lower (i.e., more severe) with higher compared to with lower approach speed and without compared to with image occlusion, indicating that subjects used smaller safety margins if the image was occluded.

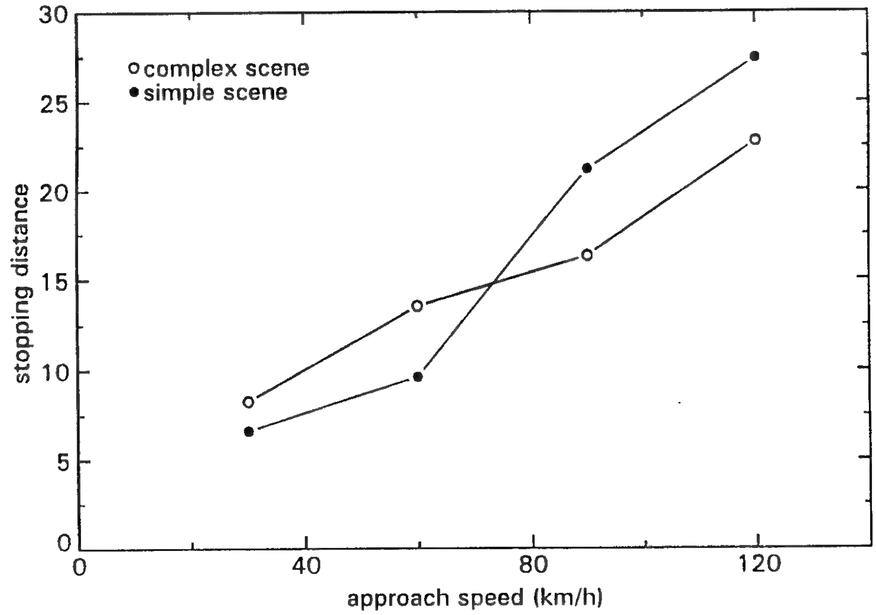

Fig. 7 Stopping distance as a function of approach speed, separately for each level of occlusion duration.

In Fig. 7 mean stopping distance is plotted against approach speed, separately for each level of occlusion duration. There were significant main effects on stopping distance of approach speed [$F(3,33)=27.9$, $p<0.01$] and occlusion condition [$F(1,11)=5.6$, $p<0.05$]. Subjects stopped further from the stationary vehicle with higher approach speeds. Stopping distance was higher without compared to with occlusion.

Table II The percentages of collisions in Experiment 2, separately for the different approach speeds and occlusion conditions.

speed (km/h)	*collision percentage*	
	normal	occlusion
30	4.17	3.13
60	4.17	15.63
90	8.33	30.21
120	17.71	40.63

Table II shows the collision percentages for the different approach speeds in each occlusion condition. Effects on collision rates were analyzed by means of a log-linear analysis with scene complexity, field of view, approach speed and occlusion. In the occlusion condition many trials ended with a collision with the stationary vehicle (up to over 40% when approaching at 120 km/h). Note that subjects did not receive feedback on their performance after the image was occluded, so that there was no opportunity for them to correct their behavior. Significantly more collisions occurred when the image was occluded compared to when it was not (22.4% compared to 8.6%; $\chi^2=31.5$, $p<0.01$). The effects on collision

percentages were analyzed separately for each of the occlusion conditions. Without image occlusion, there were significant effects on collision percentage of scene complexity (5.7% with the complex scene compared to 11.5% with the simple scene; $\chi^2=4.1$, $p<0.05$) and of approach speed (see Table II; $\chi^2=14.0$, $p<0.01$), but not of FOV. With image occlusion, there was only a significant effect of approach speed (see Table II; $\chi^2=51.3$, $p<0.01$), not of scene complexity or FOV. Note that in the present experiment collision levels were higher compared to in Experiment 1. This is the likely consequence of the availability of feedback on only half of the trials, which may have delayed or disturbed the learning process.

3.4 Discussion

If the image was not occluded, performance was similar to in Experiment 1. Larger safety margins were used with higher approach speed, resulting in higher TTC_{br} and TTC_{min}, and larger stopping distances. Occluding the image after the onset of a braking maneuver strongly affected performance. Drivers decelerated more slowly, kept smaller safety margins, stopped closer to the stationary vehicle and caused more collisions. Apparently drivers wait for a cue that tells them to timely come to a complete standstill, and fail to do so when such information is lacking. A possible effect of TTC underestimation or safety-biased behavior after image occlusion would have yielded effects in the opposite direction, and therefore cannot have contributed to the present findings.

The results also show that FOV and scene complexity do not effect collision rate if the image is occluded, which confirms the finding that these variables—presumably important to TTC perception—are only relevant within relatively short distances.

4 GENERAL DISCUSSION

The present results (Experiments 1 and 2) showed that when approaching at low speed (30 km/h) braking behavior in a driving simulator was highly similar to real-world behavior, even in non-optimal circumstances (40° field of view, simple scene), which provides a baseline validation of the TNO driving simulator. In case of higher approach speeds, however, drivers tended to be more cautious with regard to the *onset* of the braking maneuver in the simulator compared to in the field study. This difference did not depend on field of view or scene complexity. Several explanations are available. First, the resolution of the simulator image is limited, which might specifically effect perceptual information in case of higher driving speeds. Second, such an effect could also be the result of a lack of proprioceptive self-motion information in a fixed based driving simulator. Future studies will have to be aimed at the effects of image resolution and of proprioceptive information such as provided by a moving base.

The present study shows that horizontal field of view is relevant to at least some aspects of driving a vehicle simulator: with 120° FOV drivers need a smaller safety margin *during* the

braking maneuver and still cause fewer collisions compared to with 40° FOV. Note that this effect occurred in a task where there was no increased preview on the course of the road or on other traffic with a larger FOV. On the other hand, judging when to start braking and controlling the ongoing braking maneuver were independent of horizontal field of view (40° *vs* 120°) and scene complexity (bare road without delineation *vs* delineated road with reflector posts, trees, and houses). Increasing field of view or scene complexity did not help drivers to judge the moment to start braking.

This does not necessarily imply that FOV and scene complexity are also irrelevant to performance on other long-range driving tasks. For instance, as soon as a driver needs to turn right or left, or anticipate the behavior of sideway traffic, a larger FOV enables the driver to have a larger preview. Yet, the perception of speed and/or optic flow does not improve with field of view or scene complexity at large distances to the relevant location in the scene. On the basis of the present results it can be concluded that, as long as there are no anticipatory advantages of a larger FOV (as in interaction with other traffic, or when making a 90° turn) performance is not better with a 120° FOV compared to a 40° FOV at large distances.

Experiment 2 showed that visual information is used to guide the braking maneuver after its onset. Without visual feedback, drivers tended to brake too slow and to overshoot their intended stopping position.

In line with the results of Van der Horst (1990), the present results do not support the idea that only TTC is used to guide the onset and going-on of a braking maneuver. Results showed that, depending on approach speed, different TTC criteria were used. Yet, the possibility of using *only* TTC information without any reference to speed or distance formed the attractiveness of Lee's (1976) model of braking behavior. Since, when braking for a stationary vehicle, the approach speed is always available on the speedometer, this information can be used relatively easily to develop a more efficient (and more complex) braking strategy. Note, however, that such a strategy is not a priori superior to using speed and distance, since then also two perceptual variables are involved. Possibly this is different for other driving tasks. For instance, when braking to avoid a collision with a moving object, relative speed is no longer a priori available. The finding that FOV did have an effect at short distance (collision risk or stopping distance) may reflect that TTC is used at short distances, when the TTC stimulus is larger and possibly more easy to use. Another possibility is that (like in the study of Janssen *et al.*, 1976, in a car-following task) background information is not used for TTC perception, which would explain the absence of effects of scene content and field of view on TTCbr (note that FOV did not have an effect on estimated TTC in Experiment 3).

Generally, collision avoidance systems use a constant TTC criterion for warning the driver (e.g., 4 to 5 s; Van der Horst & Hogema, 1994). The present results (and the Van der Horst, 1990-results) suggest that collision avoidance systems should use different TTC criteria for different relative speeds. Although an ongoing braking maneuver in real traffic may be controlled by means of a constant TTC criterion (the TTC_{min}, Van der Horst, 1990,

1991) the timing of the onset of a safe braking maneuver is not determined by TTC alone, and a CAS should function accordingly.

It can be concluded that the validity of the simulator regarding braking before a stationary vehicle increased with increasing field of view, although only with respect to the control of the braking maneuver, and not with respect to the timing of its onset. For the present task scene complexity showed not to be important. Further research will have to be dedicated to the effects of proprioceptive information and image resolution.

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[1] On January 1, 1994 the name "TNO Institute for Perception" has been changed to "TNO Human Factors Research Institute".

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Soesterberg, 6 June 1996

Drs. N.A. Kaptein
(1st author)

Dr. J.E. Korteling
(Project Manager)

VERZENDLIJST

1. Directeur M&P DO

2. Directie Wetenschappelijk Onderzoek en Ontwikkeling Defensie

3. { Hoofd Wetenschappelijk Onderzoek KL
Plv. Hoofd Wetenschappelijk Onderzoek KL

4. Hoofd Wetenschappelijk Onderzoek KLu

5. { Hoofd Wetenschappelijk Onderzoek KM
Plv. Hoofd Wetenschappelijk Onderzoek KM

6, 7 en 8. Bibliotheek KMA, Breda

9. Maj. P.J.H.M. van der Burgt, Hoofd Bureau COO-SIM, Koninklijke Landmacht, Staf OCVVR, Vught

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